Numerical Studies of Acoustic Propagation in Shallow Water

John B. Schneider

School of Electrical Engineering and Computer Science
Washington State University
P.O. Box 642752
Pullman, WA 99164-2752
Phone: 509 335 4655, FAX: 509 335 3818, Email: schneidj@eecs.wsu.edu
Award Number: N00014-96-1-0790
Web Site: http://www.eecs.wsu.edu/~schneidj/

LONG-TERM GOALS

To develop "exact" numerical methods and visualization techniques that can be used to study the propagation of acoustic energy in shallow water in the time-domain. Exact in this contexts means the methods place no restrictions on the underlying physics of the environment.

OBJECTIVES

To develop new, and enhance existing, numerical methods; to establish the accuracy, robustness, flexibility, and tractability of these methods; and to apply these methods to meaningful practical problems. Furthermore, to develop techniques for the visualization of propagation of vector and scalar fields in complicated environments.

APPROACH

We have focused our attention on the development and use of finite-difference time-domain (FDTD) methods. These time-domain techniques, which are flexible, robust, and generally simple to implement, have previously been used by the electromagnetics community to solve a wide range of problems. However, FDTD methods have not been widely used by the acoustics community and, thus, the ability of these methods to solve accurately many of the problems related to propagation in a shallow water environment is the subject of continuing research.

WORK COMPLETED

Fundamental aspects of the discretized worlds were studied and quantified; FDTD algorithms were developed; the corresponding computer programs were written; and information was disseminated via journal publications, conference presentations, and the Web.

RESULTS

Numerical methods, such as the FDTD method, model a finite physical space. In order to simulate the behavior of an unbounded space, the computational domain must be terminated with a suitable "absorbing boundary condition" (ABC). We demonstrated the application of a new ABC to 3D acoustics problems [*JASA*, **104**(2):686–693, 1998]. This ABC is attractive in that, not only does it provide much greater ac-

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curacy than older ABC's, it is much simpler to implement than other high-performance grid-termination schemes (such as the perfectly matched layer) [*IEEE Microwave and Guided Wave Let.*, **8**(1):55–57, 1998].

The standard FDTD scheme approximates hard and pressure-release boundaries (such as pertain at an impenetrable bottom or at the air-sea interface) using a staircase representation. We presented a simple technique to improve the representation of pressure release boundaries in 3D acoustic simulations [*JASA*, **104**(6):3219–3226, 1998]. We performed a rigorous analytic analysis of two locally conformal schemes designed to alleviate staircasing errors [IEEE AP-S International Symposium and URSI Radio Science Meeting, **4**:1816–1819, 1998, and *IEEE Trans. Microwave Theory and Techniques*, **47**(1):56–66, 1999].

We developed a new technique for introducing fields into FDTD computational grids. This technique permits the source of fields to be "transparent" so that the source itself does not interfere with the propagation of fields. Publications appeared which described both the behavior of individual transparent sources [*JASA*, **103**(1):3219–3226, 1998] and arrays of transparent sources (or transparent screens) [*IEEE Trans. Antennas Propagat.*, **46**(8):1159–1168, 1998].

Previously we firmly established the ability of the FDTD method to model accurately scattering from randomly rough pressure-release surfaces. We have also made significant progress in establishing the use of FDTD methods for elastic rough surfaces [*Proc. 135th Meeting Acoust. Soc. Am.*, **4**:3025–3026, 1998, and a paper in preparation for submission to *JASA*].

Furthermore, our investigations have led to a new understanding of the way in which waves propagate in the discretized world of the FDTD grid. We have shown that, counter to previous thought, FDTD grids support, and indeed require, waves that propagate faster than their counterparts in the physical world. With this new understanding, it is possible to derive expressions for the fields that will exist in a (uniform) grid without actually having to perform an FDTD simulation [*IEEE Microwave and Guided Wave Lett.*, **9**(2):54–56, 1999; IEEE AP-S International Symposium and URSI Radio Science Meeting, **1**:184–187, 1999; and a paper submitted to *IEEE Trans. Microwave Theory and Techniques*]. This may prove to be significant in many aspects of numerical modeling including the way in which energy is introduced into the grid and the way in which grids are terminated. We have also discovered another fundamental way in which the discretized world differs from the physical world and have shown how simulations which include lumped elements should be modified to account for this difference [*IEEE Trans. Microwave Theory and Techniques*, **47**(1):56–66, 1999].

Finally, we have done numerous tests comparing the relative merits of several FDTD schemes [IEEE AP-S International Symposium and URSI Radio Science Meeting, **1**:166–171, 1999; and a paper in preparation for submission to *IEEE Trans. Microwave Theory and Techniques*]. These comparisons provide insights into the techniques that are not easily garnered from the publications which originally present the techniques.

(The full citations for the work described above, as well as for additional publications acknowledging ONR funding, are given below.)

IMPLACT/APPLICATIONS: Accurate and flexible numeric methods give one the ability to conduct any number of experiments without having to resort to actual field experiments, i.e., the experiment is conducted in the computer. Although numerical methods will never supplant field experiments, numerical methods (when used within their "region of validity") do provide an extremely cost-effective means of conducting controlled experiments. Our work will enable more accurate and more efficient numerical solutions to a wide range of problems in acoustics, electromagnetics, and continuum mechanics.

TRANSITIONS: Much of the knowledge we have gained has been disseminated via publications and conference publications. Additional material is available via the Web (please refer to Web site given in the header).

RELATED PROJECTS: This work is related to research being conducted in both high-frequency acoustics and long-range propagation. Numerical models, such as the FDTD method, can be used to predict the fields scattered from small objects under short-wavelength insonification or the propagation of long-wavelength signals over limited regions of the ocean. Additionally, this work is related to the work being conducted by several other ONR-sponsored researchers including Shira Broschat, Eric Thorsos, and Philip Marston.

PUBLICATIONS

- F. D. Hastings, J. B. Schneider, S. L. Broschat, and E. I. Thorsos, "A Comparison of the Finite-Difference Time-Domain and Integral Equation Methods for Scattering from Shallow Water Sediments," abstract: *J. Acoust. Soc. Am.*, vol. 103, no. 5, pt. 2, pp. 3095; proc. paper: *Proc. 135th Meeting Acoust. Soc. Am.*, vol. 4, pp. 3025–3026, Seattle, WA, Jun. 1998.

- J. B. Schneider and C. L. Wagner, "Analytic Analysis of the CP-FDTD and C-FDTD Methods for Offset Planar Boundaries," IEEE AP-S International Symposium and URSI Radio Science Meeting, vol. 4, pp. 1816–1819, Atlanta, GA, Jun. 1998.

- J. B. Schneider, C. L. Wagner, and S. L. Broschat, "Implementation of Transparent Sources Embedded in Acoustic Finite-Difference Time-Domain Grids," *J. Acoust. Soc. Am.*, vol. 103, no. 1, pp. 136–142, 1998.

- O. M. Ramahi and J. B. Schneider, "Comparative Study of the PML and C-COM Mesh-Truncation Techniques," *IEEE Microwave and Guided Wave Let.*, vol. 8, no. 1, pp. 55–57, 1998.

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- K. L. Shlager and J. B. Schneider, "A Survey of the Finite-Difference Time-Domain Literature," in *Advances in Computational Electromagnetics: The Finite-Difference Time-Domain Method*, A. Taflove editor, Artech House, Boston, MA, chap. 1, pp. 1–62, 1998.
- C. J. Railton and J. B. Schneider, "An Analytical and Numerical Analysis of Several Locally-Conformal FDTD Schemes," *IEEE Trans. Microwave Theory and Techniques*, vol. 47, no. 1, pp. 56–66, 1999.
- C. L. Wagner and J. B. Schneider, "Divergent Fields, Charge, and Capacitance in FDTD Simulations," *IEEE Microwave and Guided Wave Lett.*, vol. 9, no. 2, pp. 54–56, 1999.
- J. B. Schneider and C. L. Wagner, "FDTD Dispersion Revisited: Faster-than-Light Propagation," *IEEE Microwave and Guided Wave Lett.*, vol. 9, no. 2, pp. 54–56, 1999.
- K. L. Shlager and J. B. Schneider, "Relative Accuracy of Several Low-Dispersion Finite-Difference Time-Domain Schemes," IEEE AP-S International Symposium and URSI Radio Science Meeting, vol. 1, pp. 168–171, Orlando, FL, Jul. 1999.
- J. B. Schneider and R. J. Kruhlak, "Inhomogeneous Waves and Faster-than-Light Propagation in the Yee FDTD Grid," IEEE AP-S International Symposium and URSI Radio Science Meeting, vol. 1, pp. 184–187, Orlando, FL, Jul. 1999.
- J. B. Schneider and R. J. Kruhlak, "Dispersion of Homogeneous and Inhomogeneous Waves in the Yee Finite-Difference Time-Domain Grid," submitted to *IEEE Trans. Microwave Theory and Techniques*.